WEATHER AND FALL MIGRATION OF HAWKS AT CEDAR GROVE, WISCONSIN

Helmut C. Mueller and Daniel D. Berger

The data for this report were obtained during a hawk-trapping and banding program conducted at the Cedar Grove Ornithological Station located on the west shore of Lake Michigan some 45 miles north of Milwaukee, Wisconsin. This area has been known for its spectacular hawk-flights since 1921 (Jung, 1935), and the Milwaukee Public Museum operated a hawk-banding station there for a number of years prior to World War II. Our banding program and migration studies were established in 1950 and are still in progress. The observations reported herein are from the autumns of the years 1952 through 1957.

Evidence of migration is obtained in two ways: (1) by directly observing birds in flight (visible migration) and (2) by noting the fluctuations in numbers of individuals and species in an area. Neither method offers a direct means of determining the factors operative in the inception of migration.

As Brewster (1886) and many others since have emphasized, the weather conditions at the bird's point of departure are important factors in bird migration. Unfortunately, birds have rarely been observed in the process of departing, and inferring the location of departure areas is fraught with difficulties. This is particularly true of analyses based on the presence and numbers of migrants in an area since the direction of arrival is also unknown. A concentration of grounded migrants may be the result of migrating birds encountering unfavorable weather (Bagg et al., 1950; Imhof, 1953; Dennis, 1954). Under other conditions these birds might have passed over unnoticed. Visible migration observations, on the other hand, are almost invariably conducted at localities on a coast, mountain ridge, or other "guiding line." Such observations present a biased picture of the numbers of migrants in an area and may give misleading evidence concerning the migratory direction of the birds.

The literature dealing with relationships of weather and bird migration is varied and extensive. A survey of the earlier works and a brief introduction to modern meteorological concepts can be found in the paper by Bagg et al. (1950).

Modern meteorological analysis is based on the concept of large moving air masses. The surface between two dissimilar air masses is termed a "front." At a given altitude an air mass has approximately the same characteristics throughout its extent, and frontal zones usually have about the same configuration for great distances along the front. Changes in such variables as temperature, wind direction, etc., can largely be attributed to the movements of air masses and fronts. Thus, information of the composition and the movement of air masses is essentially a summary of the temporal and spatial occurrence of most of the meteorological variables likely to be of interest in migration-weather analyses.

Recent investigators of nocturnal migration have correlated the following meteorological factors with the arrival of migration "waves": (1) Air mass and frontal movements (Bagg et al., 1950; Bennett, 1952; Devlin, 1953; Bagg, 1958; Baird et al., 1958; Newman, 1958). (2) Following winds (Robbins, 1949; Bagg et al., 1950; Bergman, 1951; Devlin, 1953 and 1954; Raynor, 1956; Newman, 1958). (3) Temperature (Robbins, 1949; Bergman, 1951). (4) Stable (nonturbulent) air flow (Raynor, 1956). Correlations derived from telescopic observations of birds seen crossing the face of the moon generally agree with those of the students of the arrivals of migration "waves" (Lowery, 1951; Lowery and Newman, 1955).

Only a few attempts have been made in North America to correlate diurnal visible migration with meteorological variables. Hochbaum (1955) correlated major fall waterfowl flights with rising barometer, falling temperature, decreasing humidity, and northwest winds. Ball (1947) found that Red-breasted Nuthatches (*Sitta canadensis*) migrated in periods of clear weather following intervals of inclement conditions. European workers have correlated visible migration with almost all conceivable meteorological factors: e.g., barometric pressure (Griffin and Nisbet, 1953), calm weather (Williamson, 1953), wind direction (Rudebeck, 1950), temperature change (Bergman, 1951), and constant temperature (Ritchie, 1940). Jenkins (1953) correlated migration "waves" of the fall of 1951 for northwest Europe individually with several of these semi-independent variables. In addition, it must be remembered that the physiological and behavioral state of the bird underlies all migration activity and sets the basic seasonal rhythm. Farner (1955) can be consulted for a review of the work concerned with the physiological factors influencing *Zugdisposition*.

A portion of this chaos of interpretations of migration and weather patterns can be attributed to geographical differences in migration patterns, and a part to differences in behavior of the species involved. Hinde (1951) offers an explanation that simultaneously could include several weather factors. He hypothesizes that migration results from the additive effects of both the "internal drive" and the various external factors (law of heterogeneous summation, Tinbergen, 1951:81). Thus, if the internal drive is low, even an optimal combination of external factors may be insufficient to cause migration; when the internal drive is high, any one of several stimuli may suffice. Since the internal rhythm probably varies slightly from year to year, we would expect different responses to any given set of weather conditions (Nisbet, 1957).

An alternative (and, to us, more attractive) view is that the impetus for migration lies entirely in physiological factors and that weather acts simply to aid, permit, halt, or otherwise modify the pattern of migration. The ultimate "cause" of migration undoubtedly lies in the evolutionary adaptation by selection to the breeding cycle and the availability of food, etc. (Baker, 1938; Lack, 1950). Response to a given set of meteorological conditions might be also selected for, if these conditions provide for greater survival of migrants (Nisbet, 1957).

A high correlation between a given meteorological factor and bird migration does not necessarily imply a direct causal relationship. Consider, for example, the following simplified illustration: in autumn migration usually occurs during periods of dropping temperatures and northerly winds. The birds may be responding to the temperature drop or to the effects of temperature on the food supply. Alternatively, the birds may be migrating on northerly winds simply because these following winds aid southerly passage. The correlation with temperature may thus be coincidental, or the temperature drop may serve as a "cue" announcing the onset of northerly (favorable) winds. The above can easily be further confounded by the addition of other meteorological factors.

Hawks, because of their large size and tendency to become concentrated at certain points, are extremely favorable material for a study of weather and migration. Autumn hawk-flights, studied at a number of localities in eastern North America, have been correlated with the following weather conditions: (1) west or northwest winds: Connecticut (Trowbridge, 1895, 1902); Fisher's Island, New York (Ferguson and Ferguson, 1922); Cape May, New Jersey (Stone, 1922, 1937; Allen and Peterson, 1936); Hawk Mountain, Pennsylvania (Broun, 1948, 1951); West Virginia (De Garmo, 1953); Maryland (Robbins, 1956); north shore of Lake Erie (Gunn, 1957); north shore of Lake Superior (Hofslund, 1958). (2) A low-pressure system to the north (Broun, 1951; De Garmo, 1953). (3) Decrease in temperature (Ferguson and Ferguson, 1922; Robbins, 1956). (4) Rising barometer and (5) cold front passage (Robbins, 1956). These weather conditions often occur together, and it is difficult to decide which one or several in combination are finally responsible for initiating a flight.

OBSERVATIONS

A dawn-to-dusk watch was maintained on most of 256 observation days; however, on days with little or no migration the observations often became sporadic. At the worst, observations were made with sufficient frequency to make it exceedingly doubtful that more than a dozen hawks passed by unseen on any observation day. For three of the years (1953, 1954, and 1955), observations were made essentially on every day in the period from 1 September through 25 October. In the other three years, observations

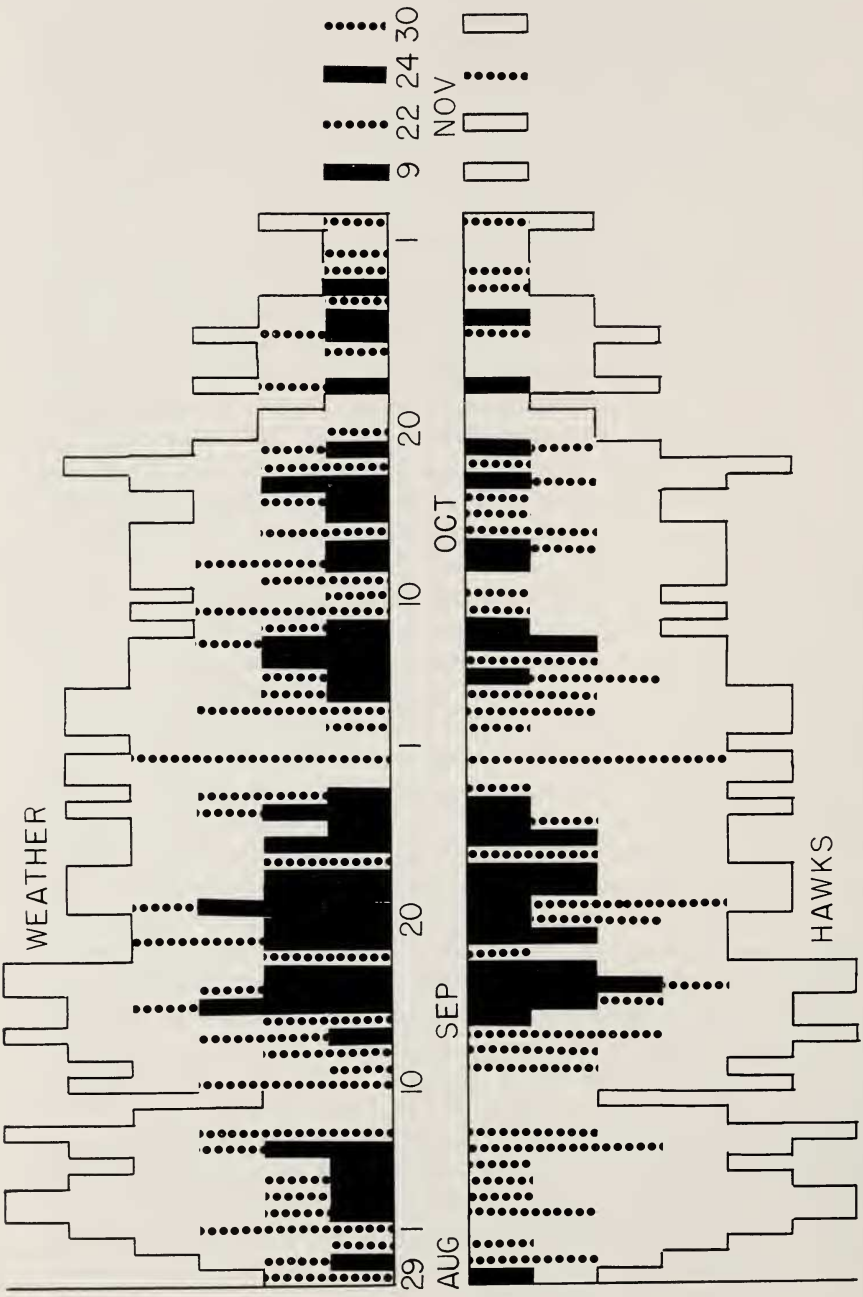

Fig. 1. Relative occurrence of observation, hawk flights, and weather suitable for hawk migration during 1952–1957. Black bars indicate number of days having Class A weather (above the date line) and the number of days having Class I flights (below date line). Similarly, dotted bars indicate Class B weather (above) and Class II flights (below). White bars indicate the number of observation days having unsuitable weather (above) and less than 25 hawks (below).

Table 1

Numbers of Hawks Observed at Cedar Grove in Autumns of 1952–1957

Broad-winged Hawk (*Buteo platypterus*)	15,965
Sharp-shinned Hawk (*Accipiter striatus*)	8,524
Red-tailed Hawk (*Buteo jamaicensis*)	1,407
Marsh Hawk (*Circus cyaneus*)	1,115
Pigeon Hawk (*Falco columbarius*)	798
Sparrow Hawk (*Falco sparverius*)	370
Cooper's Hawk (*Accipiter cooperii*)	268
Osprey (*Pandion haliaetus*)	186
Peregrine Falcon (*Falco peregrinus*)	150
Red-shouldered Hawk (*Buteo lineatus*)	72
Rough-legged Hawk (*Buteo lagopus*)	39
Goshawk (*Accipiter gentilis*)	19
Turkey Vulture (*Cathartes aura*)	17
Swainson's Hawk (*Buteo swainsoni*)	7
Bald Eagle (*Haliaetus leucocephalus*)	6
Golden Eagle (*Aquila chrysaetos*)	2
Prairie Falcon (*Falco mexicanus*)	1
Unidentified	115
Total	29,061

were somewhat biased in favor of what we assumed to be good weather. The seasonal distribution of observation through the six years is presented in Fig. 1. Approximately 29,061 Falconiformes of 17 species were recorded. The species totals given in Table 1 are composed for the most part of actual counts, although careful estimates were made on three occasions when flights were too heavy for direct counting (these estimates are indicated in Table 2).

Four species account for more than 90 per cent of the individuals observed and largely determine the characteristics of the fall hawk-flight. Two of these, the Marsh Hawk and the Red-tailed Hawk, are well distributed throughout the entire fall, while the Sharp-shinned Hawk and the Broad-winged Hawk exhibit definite peaks of occurrence. The configuration and principal species components of the fall hawk-flight can be seen in Fig. 2. This illustration presents graphically the average number of hawks (Broad-winged, Sharp-shinned, and all other species totaled) seen per observation day for each calendar date through most of the season.

The meteorological data were taken largely from Weather Bureau publications (*Local Climatological Data* and *Local Climatological Data Supplement*) for Milwaukee, Wisconsin, 45 miles south of the observation point. Local weather publications for Madison, Wisconsin, 95 miles southwest, and for Green Bay, Wisconsin, 80 miles north, were also consulted. *Daily Weather*

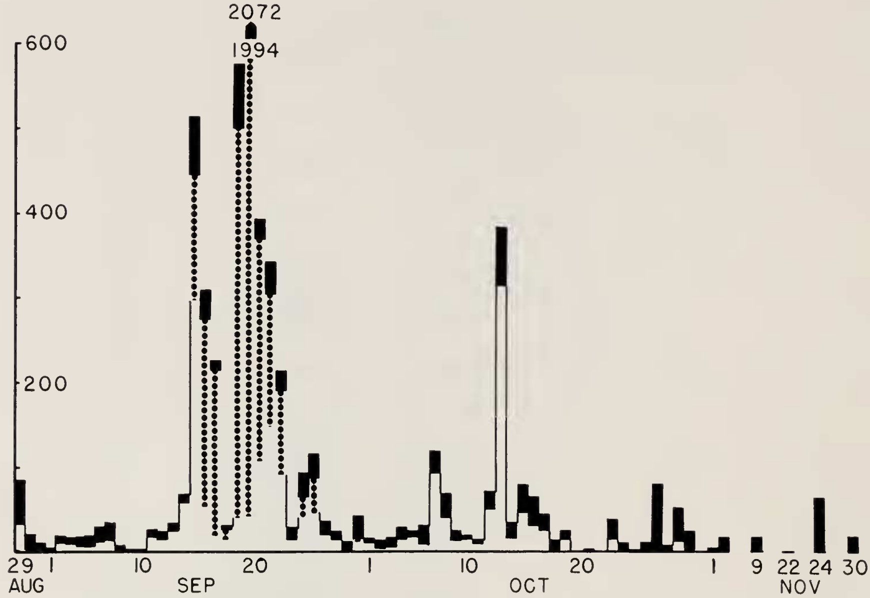

Fig. 2. Average number of hawks seen per observation day. White portion of each bar represents the number of Sharp-shinned Hawks; spotted portion, the number of Broad-winged Hawks; black portion, the number of individuals of all other species.

Maps for each of the observation days were closely examined. *Monthly Weather Review* supplied information on the movements of pressure cells. Although weather conditions were recorded at Cedar Grove, the information was not used in this report because it proved impossible to obtain consistent, accurate data with our meager equipment and varied personnel.

Although the weather conditions concerned with migration are those at the bird's point of departure, the air masses influencing the weather at the *probable* departure points of most of the birds involved in this study (i.e., to the north and west) ordinarily arrive in Wisconsin at about the same time as, or before, the birds. In the absence of more specific information regarding the areas of origin of the migrants passing Cedar Grove it would seem appropriate to restrict the analysis largely to weather conditions near the point of observation.

After a preliminary examination the observation days were placed into two classes on the basis of weather data: (A) days with westerly winds and a 1230-hour (CST) weather map similar to that shown in Fig. 3. On all these days there was a low-pressure area somewhere to the northeast of Wisconsin and high pressure to the southwest. The isobars (lines of equal barometric pressure) crossed Wisconsin on a NW–SE diagonal, and a cold

Table 2

List of All Observation Days with More Than 25 Hawks and/or Westerly Winds at Noon

Date	No. hawks	(Broad-winged)	Wind at noon	Velocity (mph)	Wind 0600 hr.	Wind prev. day	Temp. drop	No precip.	No overcast	Days since cold front	Barometer
A. With Class A weather and more than 100 hawks											
20 Sept. 1952	129	+ 7,462*	WNW	11	+	+	+	+	+	3	R
19 Sept. 1952	129	+ 2,000*	WNW	13	+	+	+	+	+	2	R
15 Sept. 1952	1,424	+ 415*	W	21	+	+	+	+	+	1	R
13 Oct. 1955	1,484*		WNW	21	+	+	+	+	+	2	R
17 Sept. 1956	161	+ 1,015	WNW	17	+	–	+	+	+	1	R
16 Sept. 1952	296	+ 782	NW	13	+	+	+	+	+	2	S
21 Sept. 1953	101	+ 801	NW	16	+	+	+	+	+	3	R
22 Sept. 1954	583	+ 285	W	17	+	+	+	+	+	2	R
23 Sept. 1957	433	+ 394	NW	23	+	+	+	+	+	2	S
22 Sept. 1957	328	+ 483	WNW	17	+	+	+	+	+	1	R
15 Sept. 1953	285	+ 349	WNW	14	+	+	+	+	+	0	F
21 Sept. 1954	432	+ 176	WNW	22	+	–	+	+	–	1	F
20 Sept. 1953	61	+ 510	NW	12	+	+	+	–	–	2	F
21 Sept. 1952	87	+ 355	WNW	17	+	+	+	+	+	4	R
26 Sept. 1954	234	+ 159	NW	14	+	+	–	+	+	2	F
16 Sept. 1957	86	+ 195	WNW	20	+	+	+	+	+	1	R
12 Oct. 1955	260		WNW	23	+	–	+	+	+	1	F
7 Oct. 1955	244		WNW	18	+	+	+	–	–	1	F
7 Oct. 1956	243		W	15	+	+	+	+	+	1	R
25 Sept. 1953	139	+ 85	W	21	+	–	+	+	–	0	F
15 Oct. 1954	217		NW	13	+	+	+	+	+	1	R
8 Oct. 1955	204		WSW	18	+	+	+	+	+	2	R
23 Sept. 1956	117	+ 77	WNW	17	+	+	+	+	+	1	R
16 Oct. 1954	173		NW	15	+	+	–	+	+	2	F
27 Oct. 1954	158		WNW	13	+	–	+	+	+	1	R
17 Oct. 1957	145		WNW	21	+	+	+	+	–	1	R
25 Sept. 1954	139		WNW	11	+	+	–	+	+	1	R
19 Sept. 1954	135		W	28	+	–	+	+	+	1	F
27 Sept. 1953	124		WNW	5	+	–	–	+	+	1	R
23 Oct. 1953	102		NW	19	+	+	+	+	+	1	F
19 Oct. 1952	101		NW	19	+	+	–	+	+	1	S
B. With Class A weather but less than 100 hawks											
6 Oct. 1956	95		WNW	32	+	–	–	+	+	0	F
4 Oct. 1952	87		WNW	14	+	+	–	+	+	0	F
15 Sept. 1957	43	+ 32	W	15	+	–	+	+	–	0	R
4 Sept. 1953	67		NW	11	–	+	+	–	–	0	R
5 Sept. 1953	64		WNW	19	+	+	+	+	+	1	R
24 Nov. 1957	64		NW	20	+	+	+	+	+	0	R
5 Oct. 1952	63		WSW	16	+	+	+	+	+	0	R
28 Sept. 1953	63		WNW	10	+	+	+	+	+	3	F
6 Sept. 1956	61		WNW	21	+	–	+	+	+	2	R
3 Sept. 1952	59		WSW	4	+	+	+	+	+	3	R

* Estimates in part.

(Table 2 continued on next page.)

TABLE 2—*Continued.*

Date	No. hawks	(Broad-winged)	Wind at noon	Velocity (mph)	Wind 0600 hr.	Wind prev. day	Temp. drop	No precip.	No overcast	Days since cold front	Barometer
6 Oct. 1955	58		NNW	7	+	−	+	+	+	0	R
13 Sept. 1957	51		SW	13	+	+	+	+	+	2	R
29 Oct. 1954	51		WNW	20	+	+	+	+	−	0	F
2 Sept. 1952	47		WNW	24	+	+	+	+	+	2	F
2 Nov. 1952	42		WNW	12	+	−	−	+	−	0	F
30 Aug. 1955	35		W	24	+	+	+	+	+	1	F
31 Aug. 1955	30		NW	20	+	+	+	+	+	2	R
6 Sept. 1953	29		NW	2	+	+	−	−	−	2	F
17 Oct. 1954	28		NW	14	+	+	+	+	+	3	R
26 Oct. 1956	25		WNW	23	+	−	+	+	−	0	F
9 Nov. 1957	20		WNW	29	+	+	+	+	+	1	R
27 Sept. 1955	13		WSW	21	−	−	−	−	−	0	F
C. With Class B weather and more than 25 hawks											
14 Sept. 1952	298		SW	20	+	−	+	+	+	0	F
29 Aug. 1954	161		WNW	15	+	−	−	+	+	1	F
30 Sept. 1953	66 +	19	NW	10	+	+	+	+	+	2	F
18 Sept. 1956	28 +	44	SSW	16	+	+	+	+	+	2	R
7 Sept. 1953	65		WNW	14	+	+	−	+	+	3	R
9 Oct. 1955	62		SW	17	+	+	−	+	+	3	F
10 Oct. 1955	57		SW	15	−	+	−	+	+	4	R
7 Sept. 1956	57		NW	17	+	+	+	+	+	3	R
30 Oct. 1954	55		NNW	17	+	+	+	+	+	1	R
11 Sept. 1955	55		W	15	−	+	+	+	+	1	R
24 Sept. 1957	47 +	5	SSW	25	+	+	+	+	+	0	R
5 Oct. 1953	50		WSW	14	+	−	+	+	+	0	F
12 Sept. 1953	49		NNW	17	+	−	+	+	−	1	F
2 Sept. 1954	45		SW	18	+	+	−	+	+	0	F
30 Sept. 1955	43		NW	15	+	+	+	+	−	1	R
6 Sept. 1955	39		WNW	15	+	−	−	+	+	0	F
30 Sept. 1957	37		WSW	21	+	−	+	+	+	0	F
4 Oct. 1954	36		NW	9	−	+	+	−	−	1	R
7 Sept. 1954	36		WNW	15	+	−	+	+	−	2	R
13 Sept. 1953	33		NNW	12	+	+	+	+	+	2	R
16 Sept. 1955	33		SSW	18	+	+	−	+	+	1	F
24 Sept. 1955	32		NW	8	+	+	+	+	+	5	R
14 Oct. 1953	32		WSW	14	+	−	+	+	+	3	F
2 Oct. 1952	31		NW	14	+	+	+	+	−	1	R
3 Oct. 1953	29		WSW	17	−	−	−	−	−	0	F
21 Sept. 1957	27		SW	23	+	−	−	+	−	0	F
30 Aug. 1953	27		WSW	7	+	+	−	+	+	17	F
30 Sept. 1956	26		NW	12	+	−	+	+	+	1	R
D. With a warm-front passage											
14 Oct. 1954	65 (51 reverse)		WSW	23	−	−	+	−	−	0	F
3 Oct. 1954	38 (4 reverse)		SSW	17	+	−	−	−	−	0	F

(Table 2 continued on next page.)

TABLE 2—*Continued.*

Date	No. hawks	(Broad-winged)	Wind at noon	Velocity (mph)	Wind 0600 hr.	Wind prev. day	Temp. drop	No precip.	No overcast	Days since cold front	Barometer
E. With Class B weather but less than 25 hawks											
19 Sept. 1953	23		NW	6	+	+	+	+	+	1	R
9 Oct. 1957	22		NW	17	+	–	–	+	–	1	R
19 Sept. 1955	22		WNW	10	+	+	+	–	–	0	F
3 Sept. 1957	21		SW	26	+	+	+	+	+	0	F
12 Oct. 1952	21		WSW	16	+	+	–	+	+	0	F
30 Nov. 1957	19		W	21	+	–	+	+	+	1	R
18 Sept. 1953	18		SW	20	–	–	–	+	+	0	F
13 Sept. 1956	16		SW	26	–	–	–	+	–	0	F
28 Oct. 1954	15		SW	26	+	+	+	+	+	0	F
23 Oct. 1954	14		WSW	12	+	–	–	+	+	9	R
16 Oct. 1955	14		NW	16	–	–	–	–	–	5	R
28 Sept. 1952	13		SSW	21	+	+	–	+	+	0	F
27 Sept. 1952	12		SSW	18	+	–	–	+	+	2	F
18 Oct. 1952	12		WSW	24	+	–	+	+	+	3	F
15 Sept 1954	11		NNW	5	–	–	+	–	–	7	S
26 Oct. 1952	9		W	12	+	–	–	+	+	2	F
1 Sept. 1952	9		WNW	8	–	–	+	+	–	1	F
14 Sept. 1955	8		WSW	9	–	+	–	+	+	0	F
8 Oct. 1953	8		SSW	17	+	–	–	+	+	2	F
4 Sept. 1955	7		WSW	10	–	+	+	+	+	6	F
10 Sept. 1954	7		NW	12	+	–	+	+	–	2	F
10 Sept. 1955	7		NNW	10	+	+	+	–	+	1	R
12 Oct. 1954	7		SSW	26	+	+	+	+	+	1	F
25 Oct. 1957	6		NNW	16	+	+	+	+	+	1	R
9 Oct. 1954	6		SW	13	+	–	–	+	–	0	F
11 Oct. 1954	6		SW	10	+	–	+	+	+	0	F
18 Oct. 1955	5		NNW	18	–	+	+	–	+	7	R
11 Oct. 1952	5		SW	14	+	–	+	+	+	3	F
1 Sept. 1953	5		SW	16	+	+	–	+	+	18	R
29 Aug. 1953	5		WSW	22	+	+	+	+	+	16	F
12 Sept. 1954	5		SW	12	+	–	+	–	–	4	R
10 Sept. 1952	4		SW	11	+	–	–	+	+	4	F
20 Oct. 1955	2		WSW	12	–	–	–	+	+	0	F
10 Sept. 1956	2		SSW	17	–	–	–	+	–	5	F
1 Sept. 1956	2		SW	17	+	+	+	+	+	1	R
3 Oct. 1952	2		SSW	21	+	+	+	+	+	2	R
19 Oct. 1957	1		NW	5	+	–	+	+	+	3	R
22 Nov. 1957	1		WSW	18	+	+	+	+	+	3	R
31 Oct. 1954	1		W	16	+	+	+	+	+	2	R
F. Without westerly winds at noon but with more than 25 hawks											
17 Sept. 1957		140	ESE	21	+	+	+	+	+	2	R
16 Sept. 1953	8 +	129	ENE	11	+	+	–	+	+	2	R
13 Sept. 1952	91		SE	13	–	–	–	+	+	7	F
20 Sept. 1954	71		SE	12	+	+	+	+	+	2	R
26 Sept. 1953	70		SSE	18	+	+	+	+	+	1	R
13 Oct. 1954	49		ESE	13	+	+	+	+	+	2	R
12 Sept. 1952	32		ESE	15	–	–	+	+	+	6	F
11 Sept. 1952	31		SE	14	+	+	–	+	+	5	R
18 Oct. 1957	25		N	20	+	+	+	+	+	2	R

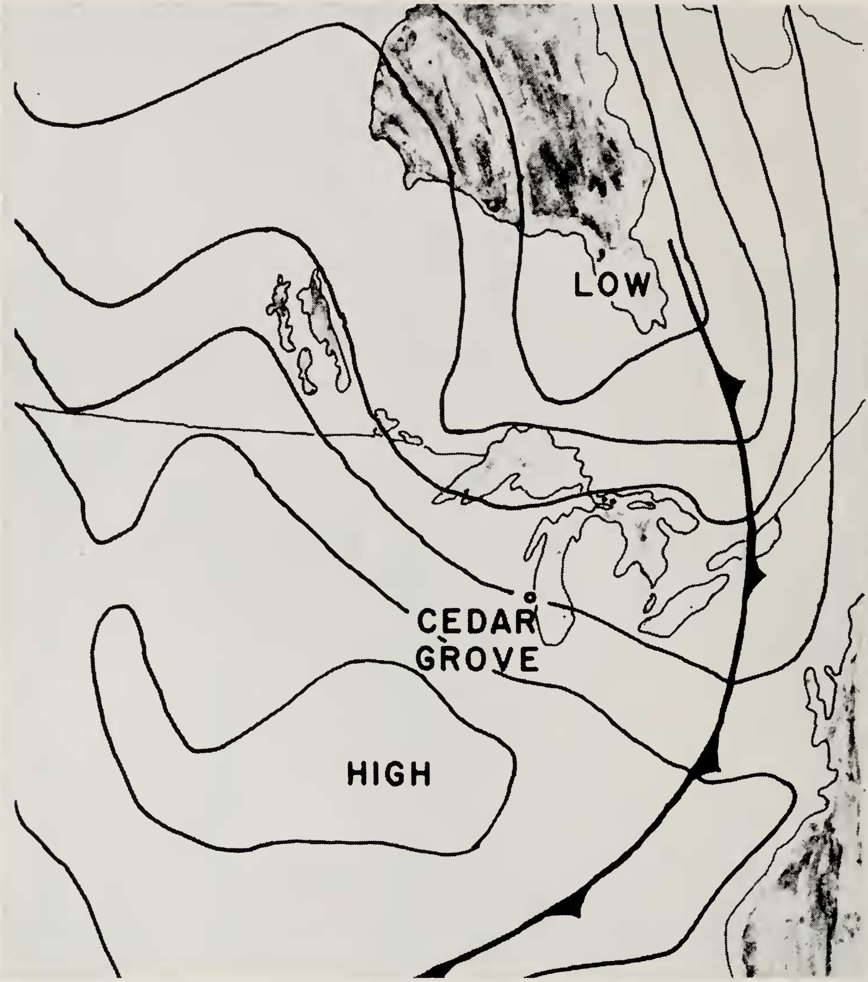

Fig. 3. An example of Class A weather. Drawn from U.S. Weather Map for 1230 hours, 13 October 1955. The line with the eastward-facing points represents a cold front; the other lines are isobars.

front lay somewhere to the south and east. (B) Days with westerly winds (between SSW and NNW) but without the above-mentioned weather map configuration. For purposes of comparing with weather conditions the observation data were grouped into two classes: (I) days on which more than 100 hawks were observed and (II) days with 25 to 100 hawks.

These four data-classes include 131 of the 256 observation days and account for 97 per cent of the hawks observed. Fewer than 25 hawks were observed on each of the remaining 125 days, and the weather was characterized chiefly by the lack of a westerly component in the wind. To simplify the presentation of the data we have chosen to omit herein these days of poor weather and few hawks.

Figure 1 gives an indication of the correlation between flights and weather of the two classes. If the correlation were perfect, the hawk and weather data would tend to appear as mirror images on this graph. While the general correlation is good, there are numerous exceptions which call for further analysis. Table 2 lists all observation days on which at least 25 hawks were seen and/or a westerly wind was blowing. In addition, the occurrence (+) or absence (−) of various meteorological variables is indicated for each of the days. In Table 3 the classes of weather and the classes of hawk-flights are combined to yield four groups of data which are then compared with the per cent occurrence of the various factors influencing migration. These factors are individually discussed in the following section.

CORRELATION OF METEOROLOGICAL FACTORS AND HAWK MIGRATION

It must again be emphasized that migration is strongly influenced by physiological variables which act independently of any short-term fluctuations of the environment. Ninety-one per cent of the Class I flights and 93 per cent of the hawks seen in this study were observed in the period 14 September through 20 October. Before 14 September and after 20 October good weather often fails to produce a good hawk flight; during the period hawks fly even if weather only begins to approach the optimum (see also Table 3, line 1).

Wind direction.—This yields perhaps the best correlation with hawk migration at Cedar Grove. Eighty-three of the 92 Class I and Class II flights occurred on days with westerly winds at noon. In six of the nine exceptions the wind was westerly earlier in the day, and the flight occurred largely before the wind shifted.

Westerly winds apparently cause southward-bound birds to drift eastward until they encounter the shore of Lake Michigan. Since hawks are reluctant to fly out over this 70-mile-wide expanse of water, their easterly drift is arrested, and the birds become concentrated along the lake shore. The lake shore acts as a "guiding" or "leading" line (*Leitlinien* of Geyr von Schweppenburg, 1929). The birds observed moving south over Cedar Grove at any given time will be those which have encountered this guiding line at some point to the north. If we assume that the hawks are more or less randomly scattered on a broad front before they encounter the guiding line, it follows that the longer the period of westerly winds the greater the number of hawks observed at a point on the guiding line. Easterly winds, on the other hand, would drift birds *away* from the lake shore.

TABLE 3

PER CENT OCCURRENCE OF INFLUENCING FACTORS FOR EACH CLASS OF DATA

Weather class No. of hawks No. of days	A > 100 31	A < 100 22	B > 25 28	B < 25 39
Within 14 Sept. to 20 Oct. inclusive.	93	36	65	51
With westerly winds at 0600 hr.	100	91	86	77
With westerly winds previous day.	77	68	61	46
With more than 100 hawks previous day.	35	5	18	3
With noon winds W to NW.	97	91	43	26
With W winds persisting since cold front.	97	91	67	41
With noon winds of velocity > 10 mph.	97	86	86	87
With noon winds of velocity > 15 mph.	68	55	61	54
With temperature drop.	84	77	64	59
Without overcast.	84	68	75	74
Without precipitation.	93	86	93	85
With rising or steady barometer in prev. 24 hours.	68	55	50	41

Good migration days almost invariably have westerly winds from daybreak on, and often the wind is also westerly on the preceding day (Table 3, lines 2 and 3). Exceptionally good flight-days are almost invariably preceded by a few hundred birds on the previous day. More than one-third of all Class I flights occurred the day after another Class I flight (Table 3, line 4). However, the frequent changes which characterize autumn weather rarely permit more than two or three consecutive Class I days.

TABLE 4

CORRELATIONS OF HAWK MIGRATION AND VELOCITY OF THE WESTERLY COMPONENT OF THE WIND

Velocity (mph) of westerly component	Wind direction					
	NNW	NW	WNW	W	WSW	SW	SSW
	A. Total number of hawks observed						
> 20	—	—	1,030	2,233	17	—	—
15–20	—	—	2,797	918	283	52	—
10–15	—	2,395	13,262	139	183	514	—
< 10	224	2,713	218	—	101	77	199
	B. Average number of hawks per observation day						
> 20	—	—	258	558	9	—	—
15–20	—	—	311	306	71	17	—
10–15	—	218	1,020	46	26	64	—
< 10	28	194	55	—	25	13	25

To illustrate the effects of wind drift let us consider a hypothetical hawk with the following characteristics: (1) a constant flight speed of 20 mph, (2) a constant flight direction (directly south), and (3) free drift with the wind. A SSW wind of 20 mph would arrest the southward progress of this hawk 18.5 miles each hour; the net southward speed of the bird would be 1.5 mph. The hawk would require 66.7 hours to move a distance of 100 miles to the south. Eastward drift would amount to 7.7 mph or 514 miles during the time required to move 100 miles southward. Distances of eastward drift for other wind directions (velocity 20 mph), derived similarly, are: SW, 283 miles; WSW, 150 miles; W, 100 miles; WNW, 67 miles; NW, 41 miles; and NNW, 20 miles.

If drift were solely responsible for the hawk migrations observed at Cedar Grove, more birds would probably be seen on SW winds than on NW winds. However, the opposite is true for most migration occurs on days with W or NW winds. Table 4 shows the correlation between wind direction, velocity of the westerly component of the wind and hawks seen per day.

Observations at Duluth, Minnesota (Hofslund, 1958), and on the north shore of Lake Erie (Gunn, 1957) show that the bulk of hawk migration occurs on northerly and westerly winds. The topography and *Leitlinien* in these localities is such that one would expect concentrations of migration on northerly, as well as westerly, winds. The only hawk migration report from the east shore of Lake Michigan known to us was on a northeasterly wind (Smith, 1904).

Since fall hawk migration apparently occurs most frequently on westerly or northerly winds, it is reasonable to suggest that following winds initiate hawk migration. However, westerly and northerly winds are associated with a complex of meteorological factors, and a review of these is necessary before a final judgment can be advanced.

Cold fronts.—The passage of a cold front in the northern United States is characterized by a rather sudden change in most measurable meteorological variables. The temperature falls, the sky rapidly clears, the humidity drops, the barometer reaches a low point and begins to rise, and the wind shifts from southerly to westerly or northerly. In fall, westerly and northwesterly winds are almost invariably associated with a recent cold front passage. Depending on the speed of movement and the paths taken by the large air masses which govern our weather, the wind may swing slowly to southwest after frontal passage, or it may shift clockwise to the south. Thus, southwesterly winds usually occur just before or several days after a cold front. More than 92 per cent of the migrant hawks observed at Cedar Grove passed on 84 days which were characterized by westerly to northwesterly winds following a cold front. Fewer than 4 per cent of the total number of hawks observed passed on 35 days with other westerly winds. Line 6 of

Table 3 gives the per cent of the days of each data-class on which the wind remained westerly or northwesterly after the passage of a cold front. Class A weather, as defined above and illustrated in Fig. 3, implies the recent passage of a cold front. In fact, the existence of westerly winds shortly after the passage of a cold front almost necessitates a weather map similar to that of Fig. 3. Three Class I flights of 35 did not have this weather map configuration, but they did have a recent cold front passage and the migration occurred in the period before a wind shift.

One Class I flight (14 September 1952) occurred in part *before* a cold front passage. The flight came at the end of an extremely atypical period of weather and hawk migration. A cold front approached Wisconsin from the northwest and became stationary just north of Lake Superior in the evening of 8 September 1952. The front remained in approximately the same place until 13 September when it began to move northward as a warm front. A new cold front moved in from the west and passed Cedar Grove at 1430 hours on 14 September. The hawk-flight began on 11 September when 31 birds were observed on a southeast wind! Even though the easterly wind persisted through 13 September, the hawk-flight slowly increased in magnitude: 32 birds on 12 September and 91 birds on 13 September. The flight continued unabated on 14 September when the cold front and an attendant rain squall scarcely interrupted the movement of 298 hawks (one bird was actually observed flying through an intense thundershower). Class A weather prevailed on 15 September, and 1,839 hawks, including a record count of 1,219 Sharp-shinned Hawks, passed over Cedar Grove.

Both the pre-frontal flight of 298 hawks and the smaller flights on the southeast winds of the preceding days are unique to our experience. We propose that the hawks began migrating in Canada with the arrival of the 8 September cold front. The birds continued south after the front halted and began to arrive in east-central Wisconsin on 10 and 11 September. In the region of Green Bay they encountered SSW to WSW winds and were drifted east to the shore of Lake Michigan. Somewhere in the 80 miles between Green Bay and Cedar Grove the wind became SE, but a few birds apparently continued to follow the lake shore at least as far south as Cedar Grove in spite of the easterly winds. On 14 September the winds were SW at both Cedar Grove and Green Bay, and the hawk-flight increased correspondingly.

Warm fronts.—The northward movement of a well-developed warm front in autumn is a rarity in Wisconsin. Only six of the 256 observation days were characterized by such a phenomenon. One of these, 14 October 1954, resulted in the only observed autumn occurrence of a reverse migration of hawks at Cedar Grove. Fifty-one of the 65 hawks seen that day were moving northward. At 0030 hours on this date the weather map showed a warm front about 50 miles south of Cedar Grove. On the 1230-hour weather map the warm front had progressed to the top of the lower peninsula of Michigan, and an eastward-moving cold front had just passed Cedar Grove. The wind was southerly all morning, shifting to westerly at noon, when the cold front passed. All birds were observed in the afternoon. The hawks probably began moving northward after the warm front in the morning but were not drifted against the lake shore until the wind shifted to the west. Once started north they apparently maintained this direction even after the cold front passed. The next day produced a southward migration of 217 hawks.

A second warm-front-date, 3 October 1954, differed considerably in the time of passage and the speed of movement of the front. The 0030-hour weather map showed a warm front a short distance south of Cedar Grove. This front remained essentially stationary and did not pass Cedar Grove until about 1130 hours. Twenty-seven birds moved southward on westerly winds before the warm front passed; four of 11 hawks after the front were moving northward. A cold front passed in the afternoon, and the following day 36 hawks moved southward on a west-northwest wind. Overcast skies persisted on both the above warm-front-days; the remaining four days with warm fronts were characterized by easterly winds and/or partly cloudy skies, and little or no hawk migration was observed.

Drost and Bock (1931) in analyzing cases of reverse fall passerine migration in Europe suggest that overcast skies may have hampered the birds' navigational ability. This idea gains support from the recent works of Kramer (1948, 1952), Kramer and Riese (1952), and Bellrose (1958), demonstrating sun-compass orientation in three orders of birds. It is reasonable to propose that on 14 October the hawks began migration in response to the warm front, and in the absence of orientation clues from the sun they flew northward with the following winds. It must be emphasized that this is not to be taken as an explanation for all reverse migration. Reverse flights often occur on clear days in spring at Cedar Grove. Fall reverse migration, because of its extreme rarity, probably merits some such special discussion as is given above.

Updrafts.—Hawks probably make considerable use of vertical air currents in their migratory passage. It is thus advantageous for the hawks if migration occurs when updrafts are available. In the lower layers of the atmosphere vertical winds are due largely to deflection of horizontal winds (as on the Appalachian ridges) and to heating of air at the surface of the ground. The latter process is at a maximum on clear days when the sun is producing a maximum of heating of the ground and when the overlying air mass is relatively cool. The clear skies and lower air temperatures usually associated with the air mass following the passage of a cold front thus provide optimum conditions for the formation of updrafts.

These updrafts tend to form into organized patterns. Under near-calm conditions these vertical currents take the form of large, columnar, chimney-like updrafts. If a horizontal wind exists, the resulting shear tilts the updrafts downwind, and with increasing wind velocity the columnar structure is disrupted. Laboratory investigations (Phillips and Walker, 1932; Graham, 1934) have shown that within a certain range of horizontal shear the convection patterns are organized into longitudinal "strip-like cells" of alternating updrafts and downdrafts.

Observations of gull-soaring over the North Atlantic (Woodcock, 1942) indicate that similar patterns of thin vertical sheets of rising air apparently occur in the free atmosphere at horizontal wind velocities of approximately 15 to 28 mph when the surface water temperature is at least 4°C higher than that of the overlying air. Woodcock noted that gulls soared in circles when the horizontal wind velocity was less than 15 mph. When the wind velocity ranged between 15 and 28 mph, the gulls soared in straight, narrow lines headed upwind. The rate of ascent was usually greater than that with circle-soaring. No soaring of any kind was observed at winds in excess of 28 mph, suggesting that convection patterns were disrupted or updrafts were of insufficient lateral extent to be useful to the gulls.

The pattern of updrafts over a land surface may be considerably different from that given above. Current theory holds that convection over a terrestrial surface takes the form of discrete bubbles or chains of bubbles of rising air (Ludlam and Scorer, 1953). Further differences would result from the irregularities of topography and varying heat capacity of a land surface. Unfortunately, we were unable to find any information about the organization and structure of updrafts in the atmosphere within a few hundred feet of the soil surface. At higher levels, however, both updrafts of the columnar or bubble form and of the longitudinal-strip type are found (Slater, 1947; Lange, 1940). It is interesting that much of the information available on updraft structure has been gathered by sailplane pilots whose numerous flights of over 100 miles are adequate evidence of the possibilities of soaring flight.

In the absence of information to the contrary, we suggest that updrafts at low altitudes over a land surface are to some degree organized in a form similar to that given by Woodcock (1942). Thus, we expect that longitudinal updraft cells exist over a suitably warm ground surface at horizontal wind velocities between approximately 15 and 28 mph. If the updrafts in these cells are of sufficient strength, a migrating hawk would be able to fly up- or downwind at considerable speed with minimal effort. Cross-wind flight could be sustained by remaining in areas of updraft as long as possible and moving through downdrafts at high speeds.

Thus, the observed correlation of hawk migration with cold fronts and with winds of 15 to 25 mph may be simply a correlation with optimal soaring conditions. The hawk-migration observations of Rudebeck (1950) in Sweden and Holstein (1946) in Denmark also seem to show better correlation with the occurrence of weather conducive to thermal updrafts than with any other meteorological factor.

Wind velocity.—There is an easily discernible difference in the reactions of birds of the genus *Buteo* and those of other hawks in regard to wind velocity. Buteos, particularly the Broad-winged Hawk, characteristically ascend circularly to great heights on a columnar updraft or rising bubble of air, then glide off in a line until a new updraft is encountered. High wind velocities break up the formation of such updrafts and inhibit *Buteo* migration. Optimum wind velocities for these soaring hawks at Cedar Grove range from 10 to 15 mph. The birds undoubtedly will fly at lower wind velocities, but the *Leitlinien* effect is rapidly reduced as wind speed decreases, and no concentrations are formed along the lake shore. The other species of hawks occur in greatest numbers at wind velocities of 15 to 25 mph (Table 3, lines 7 and 8). Winds greater than 30 mph seem to progressively inhibit all hawk migration. The Broad-winged Hawk is listed separately in Table 2 because of the above-mentioned differences in reaction to wind velocity.

Temperature.—Bird-migration might well be related to temperature change, but an uncomplicated analysis of the role of this factor is impossible. Temperature change is markedly effected by a number of seasonally independent factors. Cloud cover, for example, inhibits both nocturnal cooling and diurnal warming, severely damping variations in temperature. Wind disrupts the formation of inversions, and thus prevents extreme nocturnal cooling of low-lying areas. Thus, the influence of a moving air mass on local temperature can be completely masked or markedly exaggerated by various local conditions. The correlations were therefore not so good as conceivably might be expected, but it is possible that no better relationship exists since the aforementioned variations may well confuse the bird as well as the investigator.

Correlations of migration and daily temperature change were attempted for difference in (1) average, (2) maximum, and (3) minimum temperature from the corresponding datum for the previous day. Decrease in minimum temperature yielded the best correlation with migration, and it alone is listed in Tables 2 and 3. Temperature drop is indicated by (+) and increase or no change by (–) in Table 2.

Two seasons (1952 and 1955) were analyzed in regard to short-term temperature changes. The greatest observed drop in temperature in an hour's interval during the 24 hours prior to noon was tabulated for each observation day and compared with the number of hawks observed. A second method, utilizing the temperature change over six-hour intervals, was also attempted.

Table 5

Correlations of Temperature and Migration

Weather class / No. of hawks	A > 100	A < 100	B > 25	B < 25
Mean of departure of average daily temp. from normal.	−2.00	−2.59	−0.74	+1.82
Mean of departure of minimum daily temp. from average of minimum for previous 5 days.	−4.84	−6.79	−4.68	−1.19
Mean of departure of average 0030-hr. temp. for Duluth, Wausau, and Escanaba from same datum of prev. day.	−2.52	−1.44	−0.88	+0.44

Temperature changes between 1200–1800 hours and 1800–2400 hours of the previous day and between 0000–0600 hours and 0600–1200 hours of each observation day were tabulated. Adjustments for the normal daily temperature cycle (warming in forenoon, cooling in evening) were made in the following manner: mean temperatures of 0600, 1200, 1800, and 2400 hours were calculated for each month of observation, and the average change for each six-hour interval was determined. The net temperature change for a six-hour interval on a given day was obtained by subtracting (or adding) the average change. No reasonable correlation was found between hawk migration and these short-term temperature changes.

Finally, we tried to correlate migration with (1) the departure of the average daily temperature from normal for each day, (2) the departure of the minimum daily temperature from the minima for the previous five days, and (3) the departure of the average of 0030-hour (CST) temperatures for Duluth, Minnesota, Wausau, Wisconsin, and Escanaba, Michigan, from the corresponding datum of the previous day. The data for these considerations are given in Table 5. In each case, temperatures averaged two to three degrees lower for days on which more than 100 hawks were observed.

Although hawk-flights usually occurred after a drop in temperature and on days with relatively lower temperatures, the correlations do not appear to be of sufficient magnitude to warrant a migration hypothesis based exclusively on temperature. Trowbridge (1902) came to similar conclusions in his analysis of Connecticut hawk-flights.

Precipitation and overcast.—Table 3 (lines 10 and 11) lists the per cent occurrence of lasting overcast or appreciable precipitation in the morning hours for each class of data. Since the skies usually clear rapidly after a cold front has passed, it is interesting to note that migration occurred on some of the few days on which overcast skies persisted and some precipitation was recorded. Extended heavy rains usually ended migration, but occasional brief showers often hardly interrupted a flight.

Cloudiness reduces insolation of the ground and hence lessens air-ground temperature contrasts. This reduces, but does not necessarily eliminate, the production of updrafts. If the ground is sufficiently warmer than the invading cold air mass, updrafts will result without the aid of insolation.

Barometric pressure trends.—The only barometer-readings readily obtainable for the entire period of this study were those recorded at six-hour intervals in the *Local Climatological Data Supplement* for Milwaukee, Wisconsin. A correlation of these data with hawk counts indicates that hawks migrate more often on rising or stable barometers than when the pressure is decreasing (Table 3, line 12). This relationship is probably secondary and incidental to other factors related to the movement of the cold front. There is no sensory mechanism known by which a bird could determine absolute pressure, and there is no evidence that birds can detect the slight changes in barometric pressure that occur in nature over a period of a few hours. A bird flying from the ground to the tree tops would be subjected to an air pressure change of 0.05 to 0.08 inches of mercury; an atmospheric pressure change of this magnitude rarely occurs in an interval as short as an hour.

Air-mass movements.—A careful study of the origins and paths taken by the centers of both high- and low-pressure cells prior to their entry into the western Great Lakes area yielded no reasonable correlation with migration. The air masses in which migration occurred were almost invariably of "polar" origin, i.e., the origin was in colder, more northern regions. Beyond this restriction, it apparently made little or no difference as to where the air mass originated or as to what path it pursued before it arrived in the upper middle-west.

SUMMARY AND CONCLUSIONS

Daily counts of autumn-migrating hawks were made on 256 days in the years 1952 through 1957 at Cedar Grove, Wisconsin. Most of the migration occurred between 14 September and 20 October. More than 92 per cent of the migration occurred on 84 days characterized by westerly winds and the recent passage of a cold front. Westerly winds serve to concentrate migration along the guiding line formed by the west shore of Lake Michigan.

The fact that correlations of hawk migration with individual factors associated with frontal passage are not so good as correlations with cold fronts per se suggests that these factors act additively in effecting migration. An alternative suggestion is that weather affects migration indirectly in that it acts to modify, not produce, migration. We propose that the relation of fall hawk migration to cold fronts and winds of 15–25 mph is, simply, a correlation with the occurrence of conditions suitable for updraft formation and, hence, with good conditions for soaring and gliding.

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DEPARTMENT OF ZOOLOGY, UNIVERSITY OF WISCONSIN, MADISON; AND CEDAR GROVE ORNITHOLOGICAL STATION, RT. 1, CEDAR GROVE, WISCONSIN, 4 MAY 1960